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Federal Highway Administration

United States Environmental Protection Agency

REPORT TO CONGRESS
JUNE 1993

A STUDY OF THE USE OF RECYCLED PAVING MATERIAL

as specified in the Intermodal Surface Transportation Efficiency Act of 1991 Section 1038(b)

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16. Abstract

Section 1038(b) of the Intermodal Surface Transportation Efficiency Act of 1991 (Pub. L. 102-240) required the Department of Transportation and Environmental Protection Agency to conduct a study of asphalt pavements containing scrap tire rubber and synthesize the experience with other recycled materials.

Highway agencies have been evaluating crumb rubber modifier (CRM) technology applications at different levels of development since the 1970's. Ten CRM technologies were identified. The performance of asphalt pavements using CRM technology has been mixed. The amount of documented research on recycling CRM paving materials is limited. An analysis, using the resullts of seven studies, was conducted to compare the relative threats/risks to human heath and the environment of conventional asphalt paving to CRM asphalt paving. The health/environmental comparison was influenced by numerous variables. The data contained no obvious trends to indicate a significant increase or decrease in emissions was attributed to the use of CRM.

The highway construction industry has a long history of using recycled products for highway construction. This report summarizes some of the industries' experiences and, where sufficient information exists, it provides documentation regarding the economic savings, technical performance, threats to human health and the environment, and environmental benefits of using recycled materials in highway devices and appurtenances and highway projects.

A supporting document to this study is a research synthesis report FHWA-RD-93-088, titled "Engineering Aspects of Recycled Materials for Highway Construction."

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised June 1993)

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LIST OF ACRONYMS

AR	–asphalt rubber
ARPG	–Asphalt Rubber Producers Group
ARRA	–American Recycling and Reclaiming Association
CIPR	–cold in-place recycling
CRM	–crumb rubber modifier
DOT	–U.S. Department of Transportation
EPA	–U.S. Environmental Protection Agency
HDPE	–high-density polyethylene
HIPR	–hot in-place recycling
HMA	–hot mix asphalt
IARC	–International Agency for Research on Cancer
ISTEA	–Intermodal Surface Transportation Efficiency Act of 1991
LDPE	–low-density polyethylene
MIBK	–methyl isobutyl ketone
MSW	–municipal solid waste
MWC	–municipal waste combustion
NAPA	–National Asphalt Pavement Association
OSHA	–Occupational Safety and Health Administration
PAH	–polycyclic aromatic hydrocarbons
PEL	–Permissible Exposure Limit
PET	–polyethylene terephthalate
POM	–polycyclic organic matter
PP	–polypropylene
PS	–polystyrene
PVC	–polyvinyl chloride
RAP	–reclaimed asphalt pavement
RCRA	–Resource Conservation and Recovery Act
RUMAC	–rubber modified hot mix asphalt
SAM	–stress absorbing membrane
SAMI	–stress absorbing membrane interlayer
SEA	–sulfur extended asphalt
SHA	–State highway agency
SHRP	–Strategic Highway Research Program
VOC	–volatile organic compounds

CHAPTER 1 – INTRODUCTION

The legislative history leading up to the development of this report includes both the Department of Transportation (DOT) appropriations act for fiscal year 1992 (Pub.L. 102-143) and the surface transportation reauthorization bill (Pub.L. 102-240), titled the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). Both the appropriations act and ISTEA require the DOT to study the use of scrap tire rubber in asphalt pavements. The study required by the appropriations act was merged into the ISTEA study.

ISTEA was enacted into law on December 18, 1991. Section 1038(b), STUDIES, requires the DOT and the Environmental Protection Agency (EPA) to perform studies and report on the results of the studies to Congress within 18 months after enactment. The studies are to determine:

- The threat to human health and the environment, the ability to recycle, and the performance of asphalt pavement containing recycled rubber.

- The economic savings, technical performance, and threats and benefits to human health and the environment of using recycled materials in highways.

- The utilization and practices of all States relating to the reuse and disposal of highway materials.

The Federal Highway Administration (FHWA) and EPA created a joint technical 1038(b) study coordination group to conduct the study, to synthesize available information, and to prepare the report to be sent to Congress. The 1038(b) research study was conducted in cooperation with the States to synthesize all available State and industry information and experience. A copy of the final research study report, titled *Engineering Aspects of Recycled Materials for Highway Construction,* is appended to this report.

Other related concurrent activities through FHWA include seven national workshops on recycled rubber in asphalt technology, a symposium on other recycled materials, and direct technical support for State highway agencies and the paving industry. The seven workshops were held around the country in February and March of 1993. Over 1400 Federal, State, and local agency and industry representatives attended the 2-day programs. The recycled materials symposium is scheduled for October 19-22, 1993, in Denver, Colorado.

The body of this report is divided into two chapters: Chapter 2 - Scrap Tire Rubber and Chapter 3 - Other Recycled Materials. These chapters correspond with ISTEA Section 1038(b) subsections (1-2) and (3-4). Chapter 2 is further subdivided between FHWA's assessment of engineering and EPA's assessment of human health and the environment. Both assessments address their respective technical issues as they relate to asphalt pavement containing recycled rubber and to the recycling of those pavements. Chapter 3 is subdivided by the three specific materials identified in section 1038(b)(3), a separate subdivision for all other recycled materials, and a review of current disposal practices. In this chapter, environmental and engineering assessments are given for each subsection. Chapter 4 - Summary and Conclusions consolidates the previous chapters and is formatted by the specific issues raised in section 1038(b).

CHAPTER 2 – SCRAP TIRE RUBBER

Interest in developing alternative uses for scrap tires emerged in the mid-1980's after a number of major scrap tire stockpiles burned out of control. These stockpile fires generate air pollutants, oils, soot, and other materials that can cause water and soil contamination. Additionally, tire piles present a potential haven for the breeding of mosquitoes and habitats for other vermin. The three principal categories of alternative uses for scrap tires are whole tire applications, processed tire products, and combustion for energy recovery.(1) As of 1990, the application of these alternatives utilized approximately 17 percent of the annual scrap tire generation. Two-thirds of the scrap tires were consumed in combustion facilities, a very small fraction (less than 1 percent) was used in whole tire applications, and the balance was marketed by the processed tire products industry. The remaining 83 percent were stockpiled, placed in landfills, illegally dumped, or exported as used tires.

The potential alternative uses for scrap tires in the highway community include both whole tire applications and processed tire products.(2) Whole tire applications, like impact attenuators (crash barriers) and retaining walls, have not developed into marketable products. Several processed tire products are presently marketed in the highway industry. The types of processed tire products include shredded tires as embankment material (particularly for engineered lightweight fills), molded rubber products for railroad grade crossings and safety hardware, and crumb rubber for asphalt paving. Some of these highway applications have the potential to use significant quantities of tires in particular regions of the country. The two main uses of tires that could have a significant impact on the scrap tire problem are the recycling of scrap tire rubber and the combustion of scrap tires for energy recovery.(3) The remainder of this chapter will assess the engineering and health/environmental issues regarding the use of scrap tire rubber as an additive to asphalt paving materials.

ENGINEERING ASSESSMENT

A. Crumb Rubber Modifier

The history of adding recycled tire rubber to asphalt paving material can be traced back to the 1940's when U.S. Rubber Reclaiming Company began marketing a devulcanized recycled rubber product, called Ramflex™, as a dry particle additive to asphalt paving mixtures. In the mid-1960's, Charles McDonald began developing a modified asphalt binder using crumb rubber.(4) This product was marketed by Sahuaro Petroleum and Asphalt Company as Overflex™. The Arizona Refining Company, Inc., created a second modified binder in the mid-1970's, replacing a portion of the crumb rubber with devulcanized recycled rubber and marketing it under the name Arm-R-Shield™. Both Overflex™ and Arm-R-Shield™ were patented and eventually brought under single ownership. The companies marketing these two products founded a trade association known as the Asphalt Rubber Producers Group in the mid-1980's. Ramflex™ disappeared from the market when U.S. Rubber Reclaiming Company was sold by its parent corporation.

The other half of the history originates in Sweden. In the 1960's, two Swedish companies began developing an asphalt paving surface mixture that would resist studded tire and chain wear. The mixture included a small amount of crumb rubber as an aggregate and was called by the trade name Rubit™. In the late 1970's, this product was introduced and patented in the United States as PlusRide™ by All Seasons Surfacing Corporation. The design of PlusRide™ evolved through a series of field projects in Alaska and other States from 1979 through 1985.(5) PlusRide™ has been managed by a number of firms and is presently marketed by EnvirOtire, Inc.

With the environmental interest to find alternative uses for scrap tires and the enactment of ISTEA in 1991, asphalt technologists and rubber-recycling entrepreneurs began looking to modify or improve on the existing technologies available to add crumb rubber to asphalt paving materials. Several new technologies have emerged and are being evaluated. The initial field test sections of crumb rubber asphalt mixtures similar to PlusRide™ and McDonald technology

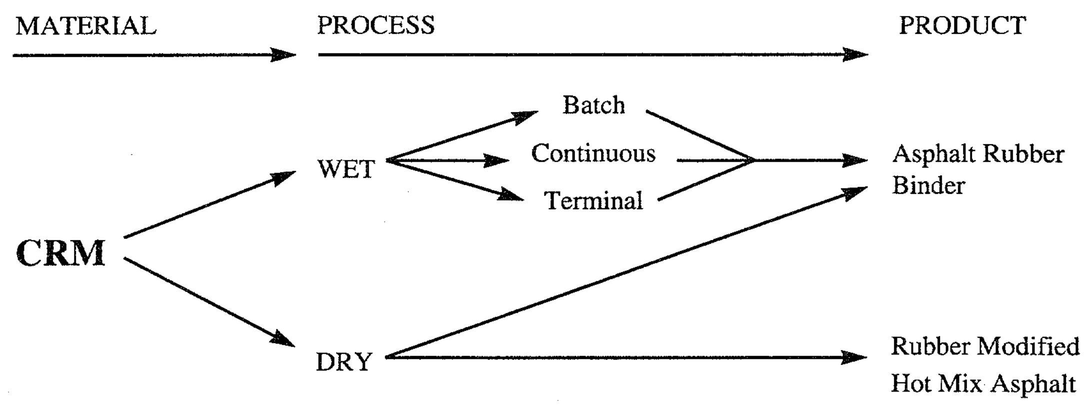

FIGURE 1. **STANDARD CRM TERMINOLOGY**

were laid in 1989 and 1990, respectively. Additional technologies have been introduced since that time, but have not been widely evaluated.

(1) Crumb Rubber Modifier Technology

Highway agencies have been evaluating crumb rubber modifier (CRM) technology applications at different levels of development since the 1970's. Reports have been written to document their findings and observations, but the diversity of terminology makes it difficult to determine the true benefit of a given product. In 1991, FHWA introduced standard terminology to improve the ability to communicate the experience of highway agencies who were evaluating different CRM technologies.[(6)] The standard terminology has been expanded to include promising new innovations. This report defines the standard terminology and summarizes it in figure 1.

Crumb rubber is recycled rubber that has been reduced in size by mechanical shearing or grinding. **Crumb rubber modifier** is crumb rubber derived from scrap tire rubber that has been reduced to particle sizes less than 6.3 mm (1/4 in) and is used in asphalt paving. The methods of producing crumb rubber impart different shape and texture characteristics to each particle. The size, shape, and texture of the CRM have a significant effect on the performance of the asphalt pavement.

CRM is incorporated with asphalt paving materials by one of two construction processes: a wet process or a dry process. The **wet process** blends the CRM into the asphalt cement to modify the properties of the binder. The method of blending can generally be divided into three categories: batch blending, continuous blending, and terminal blending. **Batch blending** defines those wet process technologies that mix batches of CRM and asphalt in production. **Continuous blending** describes those wet process technologies that have a continuous production system. **Terminal blending** is associated with wet process technologies that have products with extended storage (shelf life) characteristics and are produced at an asphalt cement supply terminal. The terminal blending technologies may use either a batch blending or continuous blending system to actually produce the product at the terminal.

The **dry process** adds the CRM to the heated aggregate or hot mix asphalt (HMA) mixture during the production of the mix. The basic concept of the dry process limits its use to the production of HMA mixtures. The flexibility of the dry process is reflected in the type and degree of modification the CRM imparts to the paving mixture. There are different types of hot mix production facilities, batch and numerous drum configurations. The type of plant may play a role in

producing different types of modified paving mixtures, but, to date, the technology and terminology do not separate the dry process construction method by facility type.

An asphalt cement binder that has been modified with CRM is called **asphalt rubber** (AR) and can be used in a number of asphalt paving products. The binder modification is achieved through an interaction of the asphalt cement and the CRM, which is commonly referred to as a **reaction**. The degree of binder modification depends on many factors, including size and texture of the CRM, the proportion of asphalt cement and CRM, compatibility with the asphalt cement, time and temperature of reaction, degree of mechanical energy during blending and reaction, and the use of other additives. Either a wet process or dry process can be used to achieve an AR binder; however, the properties of the AR can be significantly different from one design to the next and may perform differently.

A **rubber modified hot mix asphalt** (RUMAC) is defined as an HMA using a dry process where a dominant portion of the CRM particles retain their tire rubber characteristics in the final HMA paving mixture. The key to RUMAC mixtures is to design the gradation of the stone aggregate and CRM "aggregate" to achieve the desired final mixture properties. Combining the basic concepts of the dry process and RUMAC implies that a significant portion of the CRM in the mixture is relatively coarse. Variations in RUMAC mixtures are characterized by the gradation of the stone aggregate. These mixtures are classified as dense-graded, gap-graded, and open-graded.

There are presently 10 known CRM technologies at different levels of development in the United States. Table 1 provides a brief overview of each technology. As discussed above, only McDonald and PlusRide™ technologies have been evaluated for more than 5 years. Some technologies have not been field-evaluated to date. The wet process technologies are classified by the method of blending, and dry process technologies are classified by the type of paving product.

(2) Summary of Experience

The amount of experience in a given State is primarily measured by the amount of documented research reported by that highway agency, the State's response to surveys, and information supplied by industry sources. For this report, experience with CRM technology falls into three categories: extensive, limited, or none. **Extensive experience** describes those States or agencies that have made a significant effort to evaluate one or more CRM technologies, placing a series of field-evaluation projects to measure the performance. **Limited experience** describes those States or agencies that have initiated field-evaluation in the last 5 years or examined a CRM technology in the past, but did not put significant effort into the program. Table 2 summarizes the level of experience that exists for each technology based on the information available.(2)(7)(8)(9)(10)

(3) Discussion of Performance

Although a State may have a number of years of experience with a particular CRM technology, the performance of that technology can only be measured by the product/application combination for which it is used. The three basic types of asphalt paving products are sealants, thin surface treatments, and hot mix asphalt. Each of these product types can be further subdivided by the combination and proportion of materials used. A paving application is identified by the pavement distress pattern(s) that are being addressed by the project design.

Performance measurements are based on the degree of distress observed in the pavement and may include one or more different performance parameters. Typical parameters are ride, rutting, cracking, skid, splash/spray, fatigue, and aging. The four general categories of variables that will affect pavement performance are: (1) pavement design/rehabilitation strategy, (2) materials, (3) mix design, and (4) construction. The strategy chosen for a specific project must coincide with the desired performance parameters and the expected climate/traffic conditions. Proper selection of compatible, quality materials is essential. The appropriate mix design procedure must be performed correctly to determine the optimum proportion of materials and related engineering property limits. Finally, the best preconstruction design effort will not guarantee an acceptable performing pavement unless the pavement is properly constructed. Every step of the project must be accomplished with the correct engineering decisions for the pavement to achieve its intended performance. Pavements that do not perform as expected can usually be traced back to an incorrect

TABLE 1. **CRUMB RUBBER MODIFIER TECHNOLOGIES**

TECHNOLOGY	DEVELOPMENT DATE AND LOCATION / PROCESS/PRODUCT	PATENTED ? / FIELD EVALUATION	MARKETING FIRM
McDonald (1)	1960's - Arizona	patented (2)	(3)
	wet/batch/AR	extensive evaluation since 1970's	
pressure	1990 - Missouri	not patented	Dan Truax
	wet/batch/AR	has not been field-evaluated	
continuous blending	1989 - Florida	not patented	Rouse Rubber Industries (4)
	wet/continuous(terminal)/AR	limited evaluations since 1989	
terminal blending	1992 - Arizona - Washington	not patented	Neste U.S. Oil
	wet/terminal/AR	limited evaluations since 1992	
Ecoflex™	1992 - Canada	patented	Bitumar
	wet/terminal/AR	limited evaluations since 1992	
Flexochape™	1986 - France	patented	BAS Recycling (Beugnet)
	wet/terminal/AR	has not been field-evaluated in U.S.	
PlusRide™	1960's - Sweden	patented	EnvirOtire
	dry/RUMAC-gap	extensive evaluations since 1978	
generic dry (RUMAC)	1989 - New York	not patented	TAK (4)
	dry/RUMAC-gap, dense	limited evaluations since 1989	
chunk rubber	1990 - SHRP	not patented	CRREL
	dry/RUMAC-gap	has not been field-evaluated	
generic dry (AR)	1992 - Kansas	not patented	(4)
	dry/AR-open,gap,dense	limited evaluations since 1992	

(1) McDonald Technology includes both Overflex™ and Arm-R-Shield™ products.
(2) There are numerous patents related to this technology.
Some of the patents have expired, but others have not.
(3) Prior to 1993, this technology was marketed through the Asphalt Rubber Producers Group and the licensed applicators. Presently, the technology is marketed by individual applicators.
(4) Individual highway agencies are developing their own products with this technology.

decision in the process. When new materials are introduced into the mixture, each step of the process may require modification to achieve optimum performance. The performance of pavements built with CRM technology have had both successes and failures. The successes represent correct project selection, design engineering, and construction decisions. The failures generally reflect inexperience with CRM technology in project selection, design engineering, and construction decisions. Reported successes in one region of the country do not immediately substantiate success in other regions since all the variables do not remain the same.

The following paragraphs discuss the performance of the different asphalt paving applications for AR binder and RUMAC mixtures. The discussion does not distinguish between the various CRM technologies because each technology is in a different level of development. Provided two different CRM technologies can produce products with equal engineering properties, they would be expected to achieve comparable performance under the same application conditions. This discussion of performance relies on the available research reports and survey data to support the findings. The findings do not take into account those projects that document failures that are traced to improper design and/or construction practices. Those failures do not represent an accurate measure of performance.

Sealants – The use of AR sealant is common across the country. More than half the State highway agencies include an AR sealant in their pavement maintenance and rehabilitation programs. The material performs better than most other asphalt sealants.(11)

Thin Surface Treatments – The performance of AR binder in thin surface treatments has been extensively evaluated.(10) Chip seals (stress absorbing membranes - SAM) and slurry seals using AR binder have performed more effectively over certain pavement distress conditions than over others. Stress absorbing membrane interlayers (SAMI) used in two-layer and three-layer rehabilitation strategies also performed well in specific situations. Neither application appears to improve the performance of all rehabilitation strategies, particularly over pavements exhibiting dominant transverse crack or joint patterns.

Hot Mix Asphalt (7)(9) – The performance of CRM in HMA is divided between hot mix asphalt with AR binder (HMA-AR) and rubber modified hot mix asphalt mixtures (RUMAC). Each product must be further divided by the mixture type: dense, gap, or open-graded. These distinctions are essential when discussing the performance of HMA applications.

The performance of HMA-AR has not been extensively evaluated across the entire country. A significant increase in field-evaluation activity has occurred in the last 5 years. Based on limited available data, the performance of dense-graded HMA-AR has been comparable to conventional dense-graded HMA. Gap-graded HMA-AR has shown improved performance over other conventional rehabilitation strategies for certain pavement distress conditions. An AR binder used in open-graded mixtures will improve the ability to construct this surface mixture and improve pavement aging, but will not improve its principle characteristics of skid resistance and reduced splash/spray.

RUMAC mixtures have only been extensively evaluated in Alaska. These mixtures are very sensitive to proper design and construction; and, therefore, many projects have failed prematurely. Provided the mixture was properly designed and constructed, gap-graded RUMAC will perform comparably to conventional HMA and has been shown to perform more effectively for low-temperature skid resistance and rut resistance. There is insufficient development of dense-graded RUMAC to determine its performance.

Whether various CRM applications enhance cost-effectiveness varies by project. Cost-effectiveness is project specific. A cost-effective analysis must account for variables such as safety, user costs, frequency of reconstruction, and pavement performance. In the past, the initial construction cost for HMA with CRM on documented projects has generally ranged from a 50- to 100-percent increase over the conventional HMA product. Due to these high initial costs for CRM technology, most research evaluations have concluded that the specific project application has not been cost-effective. More recent projects show that the range of initial costs have been 20 to 100 percent more than the average cost experienced for conventional HMA. Given the added cost of CRM materials and processing and given the economies of scale, we would anticipate the future added initial cost would be at the lower end of this range.

TABLE 2. **SUMMARY OF EXPERIENCE**

TECHNOLOGY	EXTENSIVE	LIMITED	COMMENT
McDonald	AZ, CA	AL,AR,CO,CT, DE,FL, GA,ID, IA,KS,ME,MD, MA,MI,MS,MO, NC,NE, OH,OK, OR,PA,TN,TX, VA,WA,WI,WY	Most of the 1970's and early 1980's experience was with SAM and SAMI applications. Most of the research in the last 10 years has focused on HMA applications. Some routine use in the Southwest.
pressure react.			Has not been field-evaluated.
cont. blending		FL,IA,KS,MS, NJ, PA,VA,WA	Projects with low CRM contents are not expected to exhibit improved performance.
terminal blend		AZ,FL,OR,WA	Designed to meet local binder specifications.
Ecoflex		NC	Very limited experience.
Flexochape			Has not been field-evaluated in U.S.
PlusRide™	AK	AZ,CA,IA,MN,MT, NJ,NM,NY,NV,OK, OR,SC,UT,WA	Projects constructed prior to 1985 do not represent existing PlusRide™ design guidelines.
generic dry-RUMAC		CA,IA,IN,IL,NY,OR	Projects represent early technology development.
chunk rubber			Has not been field-evaluated.
generic dry-AR		FL,KS	Very limited experience.

This table does not reflect the use of crack/joint sealant and does not distinguish between various types of applications for each technology.

B. Recycled Crumb Rubber Modifier

(1) Recycling Variables

There are three major variables that describe the type of CRM recycling that is being evaluated. They are the materials, design, and construction technique. The CRM product being recycled may be either AR, a modified binder with CRM that has reacted with the asphalt cement, or RUMAC, a HMA with particles of CRM in the aggregate matrix. The reclaimed asphalt pavement (RAP) containing CRM (CRM RAP) may be added back into a conventional asphalt paving product or the CRM RAP may be added back into a CRM paving product. The design of the recycled CRM product will determine the proportion of CRM RAP in the mixture and the type of application (base, surface, shoulder) the mixture will be placed in. There

are three basic construction techniques used to incorporate RAP into the mixture. They are plant-recycled HMA, hot in-place recycling, and cold in-place recycling. Just as some of these variables have been demonstrated to be unacceptable for conventional RAP in certain parts of the country, they may also be limited for CRM RAP.

(2) Summary of Experience

A matrix of the recycling variables and known CRM experience is shown in table 3. Only two projects have documented the use of CRM RAP in North America. This amount of documented research is insufficient to draw any conclusions relevant to the ability to use CRM RAP on a routine basis. Furthermore, the projects were all constructed in the last 4 years, so performance evaluations are not complete. Each project is summarized below.

Ontario, Canada – As part of a planned research program, the Ontario Ministry of Transportation recycled a RUMAC [18 kg (40 lb) of CRM per ton of mix] in 1991 after the mix was in service for 1 year. The CRM RAP was added back at 30 percent into a RUMAC and placed as a surface mix. No engineering problems were noted during mixture production and placement.(12)

New Jersey – In 1992, the New Jersey Department of Transportation recycled a 1988 RUMAC [27 kg (60 lb) of CRM per ton of mix] back into a conventional surface mix. The CRM RAP was introduced through the normal RAP feeder of the drum plant as 20 percent of the total mix and no problems were noted during construction operation.(13)

HEALTH/ENVIRONMENTAL ASSESSMENT

A. Comparative Threats to Human Health and Environment

An important starting point in the comparison of threats to human health and the environment from conventional asphalt paving to asphalt paving modified with CRM is an understanding of the complexity and variability of the compositions found in asphalt cements (bitumens) used in the U.S. paving industry. Asphalt cement is not a singularly defined material with a specified or known chemical composition.

Almost all asphalt cement used today is obtained by processing crude oils. Crude petroleums vary in composition from source to source. They yield different amounts of residual asphalt cement and other distillable fractions. The amount of residual asphalt cement refined from various crude oil sources can range from 1 percent to over 50 percent, depending on whether the crude oil is light crude or heavy crude. Just as the residual asphalt cement content of the crude oils varies greatly, so does the chemical composition of the crude oils and the residual asphalt cement. The International Agency for Research on Cancer (IARC) described asphalt cements as "complex mixtures containing a large number of different chemical compounds of relatively high molecular weight: typically, 82-85% combined carbon, 12-15% hydrogen, 2-8% sulphur, 0-3% nitrogen and 0-2% oxygen."(14) IARC further chemically characterized asphalts into four broad classes of compounds: asphaltenes (5 to 25 percent by weight), resins (15 to 25 percent by weight), cyclics (45 to 60 percent by weight), and saturates (5 to 20 percent by weight). The main point is that asphalt cements are chemically undefinable mixtures that are extremely variable, so determining definite quantitative risks from asphalts or modified asphalts will be extremely difficult or impossible at this time. But, determining the relative comparative threats/risks of conventional asphalt pavements with those of CRM asphalt pavements can be done in a qualitative sense and primarily on a comparative risk basis.

Hot mix asphalt facilities are comprised of "any combination of the following: dryers; systems for screening, handling, storing, and weighing hot aggregate; systems for loading, transferring, and storing mineral filler; systems for mixing hot mix asphalt; and the loading, transfer, and storage systems associated with emission control systems."(15) Hot mix asphalt is produced by heating and drying aggregate and mixing them with asphalt cement and modifiers. There are two general types of HMA production processes: batch mix and drum mix. Each HMA mix process has numerous plant configurations and contractor modifications for materials flow and mixing.

Emissions from an HMA plant consist of steam from aggregate drying, combustion products (such as carbon dioxide and nitrogen oxides), excess combustion air, and leaks from the system (fugitive emissions). The magnitude of the relative components of emissions can vary depending on a number of factors, for

TABLE 3. **CRUMB RUBBER MODIFIER RECYCLING VARIABLES**

Type of CRM RAP		Asphalt Rubber		Rubber Modified	
Percent RAP		low	high	low	high
Recycled HMA (plant mixed)	Conventional mix			Canada	
	CRM mix			New Jersey	
Hot in-place recycling		N/A		N/A	
Cold in-place recycling		N/A		N/A	

example, the plant type and age (including combustion and emission collection systems); operating conditions (including ambient and operating temperature, moisture, and type of fuel); and materials (including aggregates, mineral fillers, modifiers, and asphalt cement). There is little or no control of fugitive emissions from HMA plants. Fugitive emissions usually originate from the dryer unit, mixing chamber, and storage silos. Stack exhaust emissions are commonly controlled at HMA plants with primary and secondary control devices. Primary control devices, such as knockout boxes or cyclones, remove large dust particles. Secondary devices, such as wet scrubbers or baghouses, remove smaller particles from the exhaust stream. The proper operation and maintenance of the pollution control equipment are key factors affecting the air emissions from the production of HMA.

In addition, differences in the wet and dry processes for CRM asphalt paving material production may impact the composition and magnitude of emissions from HMA plants. In the dry process, if the CRM is added with the aggregate into the system, the potential exists for the interaction of crumb rubber and the flame or heat from the burner to impact emissions from the asphalt plant. In both processes, the interaction between CRM and the heated asphalt binder may influence emissions from HMA production.

Asphalt cements are known to contain and emit many hazardous constituents.(14) Polycyclic organic matter (POM) and, in particular, the polycyclic aromatic hydrocarbons (PAH's) are commonly mentioned as groups of hazardous constituents of asphalts. The PAH's have been researched to the greatest degree, looking for possible carcinogenic responses in test animals and for association of carcinogenic outcomes in exposed workers. Many of these PAH's are mutagens and have been reported to cause skin cancer in treated animals and have been associated with skin and lung cancers in exposed workers.(16) (17)(18) Many of the known carcinogenic PAH's, in particular, benzo(a)pyrene, have been reported in asphalt cement itself and in its emissions.(14) Other classes of hazardous constituents of asphalt cements are the volatile organic compounds (VOC's), which contain such chemicals as benzene, benzaldehyde, alkylated benzenes, naphthalene, and alkylated naphthalenes, etc. Each of these VOC's has its own critical toxic effects after mammalian exposure. Benzene in particular is a known human carcinogen with an EPA group A cancer classification.(19)

EPA has not classified asphalt cements as to carcinogenicity. However, IARC has divided the substances via categories. In 1985 and 1987, IARC evaluated the available data on human exposures to bitumens and classified asphalt cement (bitumen) as a mixture of ingredients in IARC Group 3, inadequate evidence of carcinogenicity to humans.(20) IARC further evaluated the available animal data as limited evidence for carcinogenicity to animals for undiluted steam-refined and cracking-residue bitumens and as inadequate evidence of carcinogenicity to animals for undiluted air-refined bitumens. Applications of various extracts of steam-refined and air-refined bitumens to the skin of

mice have resulted in tumors at the site of application. This finding has lead IARC to classify only those constituent extracts of steam-refined and air-refined bitumens in Group 2B, possibly carcinogenic to humans, and is based upon sufficient evidence of carcinogenicity in those animals.(20)

In June 1992, the Occupational Safety and Health Administration (OSHA) critiqued the available animal and asphalt worker studies in their proposed rulemaking concerning the occupational exposure hazards from workers in close proximity to asphalt fumes.(21) OSHA is revisiting the Permissible Exposure Limit (PEL) for asphalt worker exposure to asphalt fumes. In their presentation of the data, OSHA evaluated how they could use available epidemiology data to determine the possibility of excess lung cancer deaths in asphalt paving workers due to occupational lifetime exposure to asphalt fumes. OSHA has not reached any final conclusions at this time. EPA has not, at this time, sufficiently studied the OSHA approach to the evaluation of the epidemiological studies.

B. Crumb Rubber Modifier

Currently, EPA has found seven studies that can be used in a qualitative sense for a weight-of-evidence comparison of the relative threats/risks of conventional asphalt pavement materials with CRM asphalt pavement materials. Six of the studies were made available to EPA as currently available emissions data from HMA production plants, recycling of asphalt pavements, or as a pilot worker exposure study rather than as final reports with specified conclusions. Six of the studies have not been available to the general public as published studies and none has been extensively peer reviewed. These studies represent a very limited data base for making this type of qualitative risk comparison and the quality control and quality assurance of the data collected have not been confirmed. Each study was conducted using:

- Unspecified asphalt cement chemical compositions.
- Different percentage of asphalt binder in the control and CRM mixes.
- Different types of asphalt paving mixtures were compared (e.g., surface treatments, open-graded, dense-graded, etc.).
- Different operating conditions existed during the comparisons.
- Varied plant configurations and emissions controls.
- Varied analytical criteria and procedures.

All the variables in these studies should alert the reader that the reported data should be viewed as relative air quality determinations and not definitive values that can be replicated with precision. There was a great amount of variability observed in most of the studies' chemical analytes, both within each study and even greater variability was observed when trying to compare between studies. With all these caveats, the seven studies will be described briefly to provide a sense of the relative comparison of the conventional asphalt paving materials with the CRM asphalt paving materials. A more complete description of the studies and the data can be found in the referenced reports.

The Asphalt Rubber Producers Group (ARPG) conducted a worker exposure study of conventional and CRM asphalt paving (using the CRM wet process).(22) Their $2^1/_2$-year study monitored workers who came into direct contact with the highest potential exposure to asphalt paving fumes, such as aggregate spreader operators, paver operators, screedmen, rakers, and bootmen. They monitored the workers for the standard OSHA contaminants of asphalt cement and compared their results to the applicable OSHA PEL's. The original authors found that exposures to both the conventional and CRM asphalt paving materials were well under the OSHA PEL's for VOC's, benzene, and PAH's. They identified a methodological problem with the determination of coal tar pitch volatiles, which they rectified by measuring individual PAH's. Their final study concluded that the "Emission exposures in Asphalt-Rubber operations did not differ from those of conventional asphalt operations." These findings have been published and released to the public. Additional analysis concerning the details of this information are provided in the research report appended.(7)

The Ontario Ministries of Transportation and the Environment have provided data on two studies that they conducted. The first study, and the most completely reported, deals with the determination of the effects of CRM (dry-process) on the stack emissions from a drum-mix HMA plant located in Thamesville, Ontario. The asphalt binder content was 5.3 percent for the conventional HMA mixes and 6.1 percent for the CRM HMA mixes. Changes in stack emission due

to the addition of CRM were difficult to assess because of this variation in binder contents between the two mixtures. It is our understanding that the Ontario Ministries are analyzing the data from this study for conclusions in the near future. Regardless, the results presented below should be looked at as preliminary until a more complete study analysis can be obtained and evaluated. The currently available results show small increases in most PAH emissions in the CRM asphalt paving data compared to the conventional asphalt paving data. The confidence intervals of the mean PAH emissions overlap and have not been assessed for binder content effects. The emissions of most VOC's were reduced in the CRM asphalt mixtures as compared to the conventional HMA. Other monitored emissions were mixed for metals and other organics. One finding among the volatile organics was the emission of methyl isobutyl ketone (MIBK) in only the CRM asphalt paving mixes.

Contained in one of the reports of the Thamesville, Ontario, study were the results of a second study of stack emissions from a batch mixing plant during mixing of conventional and CRM HMA. The study was conducted by the Regional Municipality of Haldimand-Norfolk within the Province of Ontario. Few details were available regarding the trials conducted at the plant. The currently available results show lower emission rates for most of the elements and inorganic compounds in the CRM mixes compared to the conventional mixes. Many of the individual PAH emissions were higher in the CRM mixes compared to the conventional mixes. Although emissions were higher for many PAH's, the total semi-volatile emissions were lower in the CRM mixes compared to conventional mixes. The VOC emissions were slightly higher in the CRM mixes in this study compared to the other Ontario study. These data are illustrative of the variability observed in these studies. Emissions of MIBK were found only in the CRM mixtures.

It is hard to draw any firm conclusions from the two Ontario studies because of the many apparent study variables that have not been controlled and the variable data results that question whether any trends can be found. One exception is the finding of MIBK in the CRM mixes. Although there were no specific conclusions reported from this study, a researcher, in his letter to the Library of Congress concerning his work on the Ontario studies, stated, "Based on our experience to date, we are of the opinion that there is no significant difference in the air emission profiles associated with the production of rubberized and conventional asphalt."(24)

Texas recently completed two studies comparing the stack emissions from CRM HMA to emissions from conventional HMA. One study conducted in Parmer County, Texas, involved the monitoring of stack emissions from a drum-mix plant.(25) The CRM was added to the asphalt binder using the wet process, resulting in 18 percent of the binder being CRM. The mix temperatures were varied, with the conventional mixes run at 340°F and the CRM mixes run at 340°F and 305°F, respectively. Current available results show that the particulate emissions from the 340°F CRM HMA mixture were slightly higher than the conventional HMA mixture emissions. Emissions from the 305°F CRM mix were approximately equal to the emissions from the conventional mix at 340°F. The results for the semi-volatiles were mixed, with some compounds being higher for the CRM mixes and some lower when compared to the conventional mixes at the same temperature. Even though most of the semi-volatiles were generally lower in the 305°F CRM mixes compared to the 340°F CRM mixes, a few semi-volatiles emissions were actually higher at the lower temperature. The monitored VOC's were slightly lower in the CRM mixes compared to the conventional mixes at the same temperature, but the 305°F CRM mixes were slightly higher in VOC emissions. 1,3-Butadiene was only detected in the low temperature CRM mixes. Although Texas has not reached a conclusion at this time, the data variability for the compared chemicals seems to indicate that there is little difference between the conventional and CRM asphalt mixes in this study.

The other Texas study was conducted at a drum-mix plant in San Antonio, Texas.(26) The CRM was added to the asphalt cement using the wet process, resulting in 18 percent of the binder being CRM. The HMA mix design called for 7.5- to 9-percent binder content. The emissions tests were conducted with the HMA plant operating at 325°F for conventional and some CRM mixes. Additional tests for other CRM mixtures were conducted at 300°F. Currently available results showed that the conventional mixes were higher in particulate emissions than either CRM mix. For the most part, the semi-volatiles and PAH's were comparable for both CRM mixes and conventional mixes. The VOC's were mixed with some CRM emissions

being higher than the conventional HMA mixes and some CRM emissions being lower than the conventional mixes. 1,3-Butadiene was only detected in the conventional mixes in this study. In this study, the presence of MIBK was noted in only the 325°F CRM mixtures.

The National Asphalt Paving Association (NAPA) has just completed a pilot study comparing asphalt cement fumes from the HMA plant asphalt tank headspace and from personal and area monitors during two paving operations in Valencia, California.(27) The CRM asphalt binder was prepared using the wet process containing 20 percent rubber. The HMA was placed at the paving site at temperatures between 270°F to 350°F. The conventional asphalt tank fumes contained greater levels of PAH's than the CRM asphalt binder tank fumes. The VOC's and some of the nitrosamines in the asphalt cement tanks were higher with the CRM asphalt binder than with the conventional asphalt cement. Asphalt fume, as total particulate, was reported as the only contaminant detected above the California OSHA PEL at the paving site. Confounding factors that were mentioned in this study which could potentially influence the personal and field sampling were automobile traffic, diesel exhaust, and tobacco smoke. At this time, very few conclusions can be drawn from this pilot study.

C. Recycled Crumb Rubber Modifier

The New Jersey Department of Transportation conducted a study incorporating recycled CRM asphalt pavement into a paving project in 1992. This was done to assess the concerns of the asphalt paving industry regarding the recyclability of asphalt pavements containing ground tire rubber. The project involved materials testing of the recycled CRM asphalt paving mix and monitoring the drum-mix HMA plant for air emissions. The RAP containing 3 percent CRM was introduced as 20 percent of the new HMA. "No modifications were required to the drum plant and all production procedures were normal from producing the recycled mixtures."(28) "An analysis of air quality testing performed for this project shows that PlusRide™ can be recycled within current air quality standards."(28) The air emissions study analyzed particulate, carbon monoxide, total hydrocarbon (as methane), oxygen, stack opacity, and odor.(29) The New Jersey Department of Transportation study was the only one of this type identified and is limited to the study of the recyclability of one dry process CRM asphalt pavement in a drum-mix HMA plant.

D. Conclusions

The weight-of-evidence from these seven studies, along with using the emissions data from other conventional HMA plants, show that the emissions from any HMA plant can vary widely, both in emissions profiles of contaminants and in the level of contaminants emitted. The currently available data collectively indicate that no obvious trends of significantly increased or decreased emissions can be attributed to the use of CRM in HMA pavement production. One exception is the observation of MIBK in CRM mix stack emissions in three out of seven studies. Great variability was observed within each study's chemical emission analyses and even greater variability was observed between the studies' chemical emission analyses. The emissions levels for each chemical found in these studies are within the broad range of emissions levels that have been previously reported from HMA plant operations, except for the finding of MIBK in CRM mix stack emissions in three of the seven studies.

The source of the MIBK in the three CRM mix stack emissions is not known at this time. Since MIBK was not evaluated in other asphalt studies, we cannot say that MIBK will not be found in conventional asphalt mixes and, therefore, the impact of this finding is unclear. The stack emissions of MIBK were fairly low in the three studies compared to the level of other VOC's. Studies have not found MIBK to be a carcinogen and the toxicity of MIBK is relatively similar to other VOC's found in asphalt. These findings of MIBK may warrant further investigations.

In summary, using the currently available information, we find there is no compelling evidence that the use of asphalt pavement containing recycled rubber substantially increases the threat to human health or the environment as compared to the threats associated with conventional asphalt pavements. These findings are based on the limited available data from a few studies. These conclusions are subject to revision as additional information is obtained and evaluated.

CHAPTER 3 – OTHER RECYCLED MATERIALS

Today, the United States is experiencing a dramatic increase in the amount and types of materials being discarded. This increase, coupled with the concern of society regarding environmentally safe and efficient disposal of these materials, has placed a tremendous burden on the Nation's landfills and disposal sites. In 1960, 82 million metric tons (90 million tons) of municipal solid wastes (MSW) were produced per year in the United States. This rose to 146 million metric tons (161 million tons) in 1986, and 164 million metric tons (181 million tons) in 1988.(30) In addition, other solid waste materials from agricultural, industrial, building and construction, and mining add to the solid waste stream. When added together, the total amount of solid waste produced in the United States annually is 4.1 billion metric tons (4.5 billion tons).(31)

The highway construction industry has a long history of using recycled products for highway construction. From the use of asphalt cement, a waste product from oil refinement, to the current usage of fly-ash in Portland cement concrete, the industry has used waste products to further the quality and durability of the highway infrastructure.

State highway agencies (SHA's) and private organizations and individuals have completed or are in the process of completing numerous studies and research projects concerning the feasibility, cost-effectiveness, and performance of pavements constructed using various waste products.(31) These studies attempt to mesh the need of society to safely and economically manage the increasing amount of waste materials with the continuing needs of the highway industry for better and more cost-effective construction materials.

EPA and FHWA have existing policy and technical guidance supporting the use or reuse of waste materials where technically and economically feasible.(32)(33)(34)(35) This report summarizes some of the industries' experiences and, where sufficient information exists, it provides documentation regarding the economic savings, technical performance qualities, threats to human health and the environment, and environmental benefits of using these materials in highway devices and appurtenances and highway projects.

SCOPE

Waste materials for the purpose of this report will be divided into broad categories of wastes. Table 4 is a list of the major waste categories with a specific breakdown under each major heading. The annual quantity generated by each broad category is also included.(30)(31)(36)(37)

Research into the use of waste materials is ongoing and new research findings and recommendations are being developed. To keep abreast of the current usage of waste materials in highway construction, FHWA and EPA will be conducting a symposium on "Recovery and Effective Reuse of Discarded Materials and By-Products for Construction of Highway Facilities." The primary objective of this symposium is to gather and disseminate current, state-of-the-art information on new and innovative methods for recycling discarded materials and by-products in the construction of highway facilities. All sources of information on this subject will be represented to give a broad perspective on the many ways in which recycling can benefit the highway construction industry. The 3-day symposium will be held in Denver, Colorado, on October 19 through 22, 1993.

Many of the materials appearing in table 4 have had some use in the construction of highways. These uses range from a very limited experimental basis to wide use and acceptance. Included in table 4 is a summary of some of the experiences highway agencies have had with the use and performance of these materials. However, although it can be concluded that there are many varied uses for waste materials in highway construction, this report focuses only on those uses of waste materials that have been or may be combined into asphalt concrete paving mixtures. The reason for limiting the scope of this report is to focus on those materials that may be substituted for CRM in asphalt concrete pavements as allowed in section 1038(d)(2) of ISTEA.

RECYCLED MATERIALS IN ASPHALT CONCRETE

A. Reclaimed Asphalt Pavement

(1) General

Over 80 percent of the asphalt pavement removed is reused in highway applications and less than 20 percent is disposed.[7] Most SHA's specifications permit the contractor to retain ownership of RAP. This policy permits contractor flexibility in managing equipment capabilities and material inventories in order to compete in the competitive bidding process.

There are several ways to categorize pavement recycling methods, depending on how and where the recycling is accomplished. However, the most frequently used methods for recycling asphalt pavement materials falls into three categories: plant (off-site) recycled HMA, hot in-place recycling, and cold in-place recycling.

(2) Recycled Hot Mix Asphalt

Plant-recycled HMA is a process where the existing asphalt pavement is removed, usually by a cold milling machine, hauled to an HMA plant, and processed and stockpiled at the plant yard for future use as RAP. The RAP is remixed as a component of an HMA. The percentage of RAP in a recycled mix is determined by an engineering analysis usually requiring the recycled mix to meet conventional HMA materials and mixture design properties. Experience has shown that when recycled HMA is designed to meet the same materials properties as conventional HMA, its performance has been as good as conventional HMA.

a. Recycled Hot Mix Asphalt (Conventional HMA Plants)

There are two basic types of conventional HMA plants: batch and drum dryer mixers. Conventional plants super-heat virgin or new aggregates to transfer heat to the RAP and obtain the final recycled mixture temperature. Direct flame heating of the RAP was found to further age the RAP and cause air emission problems. FHWA Demonstration Project 39 showed that "heat transfer" was the easiest method to retrofit existing plants to produce a recycled mix and meet existing air quality requirements. Batch plants usually are limited to producing mixes with a maximum RAP content of 50 percent. Dryer drum mixers are usually limited to a maximum RAP content of 50 to 70 percent.[38] NAPA reported that the production of recycled HMA was 26 percent of the total HMA production in 1985, and 23 percent in 1986.[4] NAPA also reported that the average RAP content in a recycled mix was 24 percent in 1985 and 22 percent in 1986.[40]

The SHA's that routinely permit RAP as a component in **quality** HMA production report cost savings. The Florida Department of Transportation has found that the initial construction cost of a recycled HMA project is 15 to 30 percent less than that of a conventional paving approach.[41] This range of initial cost savings is consistent with those reported and predicted by FHWA.[39] The actual savings on individual projects will be dependent on project location, plant location, materials availability and location, and asphalt cement prices, etc.

b. Recycled Hot Mix Asphalt Containing Greater Than 80 Percent RAP

Cyclean™, a proprietary hot mix plant, is a recent innovation in the HMA industry. Cyclean™ plants can recycle HMA with RAP contents in excess of 80 percent. The RAP is fed to a counter-flow dryer drum to preheat the RAP and remove moisture. Virgin aggregate, if required by mix design and evaluation, is added by a separate feed bin to the dryer drum. The RAP is heated to approximately 135°C (275°F) in the dryer drum, the RAP is fed to a microwave tunnel where the RAP is heated to 155°C (311°F). A rejuvenating agent is added and the RAP is remixed, stored, and then loaded for placement. The advantage of this plant is that the RAP is not further aged and oxidized during the reheating process.[42] One disadvantage of this process is the high cost of microwave energy.[43]

Cyclean™ has been producing recycled HMA, containing at least 80 percent RAP, for the city of Los Angeles since 1987. Performance of these recycled HMA pavements has not been documented. Recycled HMA specifications for the city of Los Angeles are different from those of most SHA's and it cannot be determined, based on documentation, whether these recycled mixtures would have met conventional HMA specifications. The Georgia Department of Transportation used the Cyclean™ process to recycle

TABLE 4. **SUMMARY OF KNOWN WASTE APPLICATIONS**

WASTE CATEGORY	ANNUAL RATES IN MILLIONS OF METRIC TONS: PRODUCED	RECYCLED	CURRENT AND PAST HIGHWAY USES: ASPHALT PAVEMENT	CONCRETE PAVEMENT	BASE COURSE	EMBANK-MENT	OTHER
AGRICULTURAL WASTES	**1,910**						
Animal Manure	1,460		NA	NA	NA	NA	AA
Crop Wastes	360		ER	ER	UN	UN	UN
Logging and Wood Wastes	64		NA	NA	NA	AA	AA
Miscellaneous Organics	27		UN	NA	NA	UN	UN
DOMESTIC WASTES	**180**						
Paper and Paperboard	66.7	16.4	NA	NA	NA	NA	LA
Yard Waste	31.9	3.8	NA	NA	NA	NA	AA
Plastic*	14.7	0.3	LR	ER	UN	UN	AR
Glass	12.0	2.4	LA	NA	LA	LA	LR
Municipal Waste Ash*	7.3		LR	ER	LA	NA	UN
Sewage Sludge\Ash	7.3		LR	LR	ER	LR	LR
Scrap Tires*	2.3	0.4	AR	ER	ER	AR	AR
INDUSTRIAL WASTE	**273**	**30**					
Reclaimed Asphalt Pavement	91	73	AA	LR	AA	AA	UN
Coal Fly Ash	45	11	AA	AA	AA	LR	UN
Demolition Debris	23		ER	UN	ER	ER	UN
Cement & Lime Kiln Dust	21	13	ER	UN	ER	ER	UN
Sulfate Waste	16		ER	ER	ER	ER	LR
Coal Bottom Ash/Bottom Slag	16	5	LR	UR	LR	ER	UN
Blast Furnace Slag	14.5		AA	AA	LR	LR	AA
Non-Ferrous Slags*	9		LR	ER	LR	UN	LR
Foundry Waste*	9		ER	UN	UN	ER	ER
Roofing Shingles	6.4		AR	UN	UN	AR	UN
Steel Slag	7.3		AR	NA	LL	AA	LA
Reclaimed Concrete Pavement	3		AR	AR	AA	AA	AA
Lime Waste	2		ER	UN	ER	ER	ER
MINING AND MINERAL WASTE	**1,640**						
Waste Rock*	930		AA	UN	LR	LR	UN
Mine Tailings*	473		AR	UN	AR	AL	UN
Coal Refuse	109		ER	UN	UN	ER	UN
Phosphogypsum*	96		UN	UN	ER	ER	UN
Washery Rejects	32		NA	NA	NA	ER	UN

<u>Key to Abbreviations</u>
AA - Accepted use; No further research suggested
AR - Accepted use; Design & performance research suggested
LA - Limited use; No further research suggested
LR - Limited use; Design and performance research suggested
ER - Experimental; Design and performance research suggested

NA - Unacceptable use
UN - Unknown use

* There are environmental concerns with this material that may require further research.

State-owned RAP into recycled HMA for pavement shoulders. The RAP content of this mix was 90 percent with 10 percent natural sand added. Testing of the recycled mixture showed that it would not have met air-void criteria in conventional HMA specifications.(44) Michigan, Pennsylvania, and Texas have also experimented with this process. These States are using the recycled mix, containing at least 80 percent RAP, in the pavement structure. These projects have been in service less than 2 years and thus, long-term performance cannot be reported.

Life-cycle costs cannot be reported without substantial performance data, however, initial construction cost savings have been reported. According to bid information from the Michigan project, the mix produced by the Cyclean™ process provided an initial cost savings of roughly $11/metric ton ($10/ton) over the engineer's estimated cost for conventional HMA. Although the recycled HMA was not bid as an alternative to conventional HMA, the engineer's estimate is usually an average of statewide or areawide bid prices as can be used to measure cost savings. The engineer's estimate for conventional HMA was $32/ton and the combined cost of the Cyclean™ recycled HMA was $21.29/ton. Bid tabulations from the Texas I-35 project showed that the Cyclean™ recycled HMA provided an initial cost savings of $6.60/metric ton ($6.00/ton) compared with bid items for conventional HMA on that project.(45) It should be noted that the quantity for conventional HMA [4,166 metric tons (4,593 tons)] is substantially less than the quantity for Cyclean™ recycled HMA [113,547 metric tons (125,190 tons)], which somewhat inflates the initial cost savings.

(3) Cold In-Place Recycling

Cold in-place recycling (CIPR) is another recycling technique that is used to rehabilitate existing pavements. Production takes place at the site of the existing pavement surface and involves milling, mixing, and placing of pavement material in the absence of heat. After placement, the material is cured so that water from the asphalt emulsion evaporates. The layer is then compacted. Further curing is necessary before placing a wearing surface and opening to heavy truck traffic. Because curing is necessary and relies on high temperatures with low moisture, this rehabilitation technique is limited to certain climates and roadway applications.(46)

The American Recycling and Reclaiming Association (ARRA) estimates that approximately 2,060,000 metric tons (2,270,000 tons) of pavement were processed as CIPR in 1991. This equates to 9,300 lane-km (5,800 lane-mi).(47) The depth of treatment is usually 50 to 100 mm (2 to 4 in). California, Kansas, New Mexico, and Oregon are frequent users of CIPR. It has been used mainly on medium to lower traffic volume roadways. New Mexico uses CIPR on Interstate highways; however, 75 to 125 mm (3 to 5 in) of hot mix asphalt are required to be placed on top of the CIPR layer to accommodate anticipated truck traffic.

Performance studies have shown that CIPR retards or eliminates the reoccurrence of reflection cracking from environmental distresses, depending on the depth of treatment versus the depth of crack.(48)(49)(50) However, research has shown that CIPR does not structurally improve the existing pavement.(48) Comprehensive nationwide information on performance of CIPR is not available and thus life-cycle costs cannot be determined. However, first cost savings of 6 to 67 percent have been reported over comparable rehabilitation strategies.(51)

(4) Hot In-Place Recycling

Hot in-place recycling (HIPR) is a third recycling technique that is used to rehabilitate an asphalt pavement. Production takes place at the paving site and involves: (1) heating the existing pavement, (2) milling, (3) adding new aggregate, asphalt cement, and/or rejuvenating agent, and (4) mixing, placing, and compacting in one pass of the recycling train. Currently, HIPR is limited to depths of 60 mm (2 in) or less. This technique is used mostly by maintenance forces to address pavement distresses confined to the surface course of the pavement [top 50 mm (2 in)].

The ARRA reported that its contractors used HIPR to recycle approximately 545,000 metric tons (601,000 tons) of existing pavement in 1991. This is roughly equivalent to 3,900 lane-km (2,400 lane-mi).(47) Performance of this technique is not widely reported. Thus far, HIPR has been used on pavements that are structurally adequate and do not require any structural improvement. The cost of this technique has varied greatly. As much as a 16-percent increase in cost has been reported and as much as 40-percent cost savings have been reported when compared to milling and replacing with conventional hot mix asphalt. Recent

reports show that cost savings of less than 10 percent have been realized.[38][52][53]

B. Recycled Glass

(1) Material Availability

Glass makes up approximately 7 percent of the total weight of the MSW discarded annually or approximately 12 million metric tons (13 million tons). Of this, approximately 20 percent is being recycled, primarily for cullet in glass manufacturing.[30] The availability of glass for use as a highway construction material is dependent upon the type and availability of collection methods used, costs, and public factors. In general, large quantities of waste glass are only found in major metropolitan areas.

(2) Experience

Many SHA's have experimented with the use of glass in asphalt pavements. Some SHA's have only performed laboratory testing while others have actual field experience. Studies indicate that at least 10 States have some experience with the use of glass in asphalt pavements.[31][36][55] Based on the experiences of the States and research completed by Hughes, Larsen, and others, the addition of glass into asphalt pavements can be accomplished successfully when limited to the following conditions:[31][36][56][57]

- The amount of glass is limited to 15 percent (by weight of total aggregate).
- The glass is crushed so that 100 percent passes the 9.5-mm (3/8-in) sieve with no more than 8 percent passing the 75-µm (No. 200) sieve.
- An anti-strip additive is added to improve resistance to moisture damage.
- HMA with crushed glass is limited to binder or base course mixes and is not used in a surface or friction course.

(3) Economics

The highway construction industry has an ongoing need for high quality aggregates. Research studies indicate that the current cost of fine aggregate for use in asphalt paving mixes is approximately $1 to $4/metric ton ($1 to $4/ton).[7] These costs include crushing and transportation to the construction site. However, in some metropolitan areas, fine aggregates can be as much as $13/metric ton ($12/ton).[54]

Glass disposal costs vary depending upon location. Disposal costs range from $22 to $55/metric ton ($20 to $50/ton).[54] The purchase price for sorted uncrushed glass varies by region, but is generally $44 to $55/metric ton ($40 to $50/ton) for clear glass, $28 to $55/metric ton ($25 to $50/ton) for brown glass, and $0 to $55/metric ton ($0 to $50/ton) for green glass.[58] In major metropolitan centers in the Northeast, unsorted uncrushed glass can sometimes be obtained at no cost.[7][59] The costs of crushing and sizing the glass for use as a highway construction aggregate will add to the purchase cost.

(4) Health and Environmental Effects

The health or environmental effects of incorporating glass into asphalt paving mixtures have not been studied. However, it is reasonable to conclude that additional stack emissions or leachate would not be a problem due to the inert nature of glass. Possible risks to human health may be in the handling and transporting of the crushed glass. This risk could be minimized by taking precautions during crushing, handling, and transporting.[54]

C. Recycled Plastic

(1) Material Availability

Plastics comprise over 8 percent of the total weight of municipal waste stream or approximately 12 percent to 20 percent of the volume.[7][30] Approximately 14.7 million metric tons (16.2 million tons) of plastics are disposed of each year with only 2.2 percent being recycled. Based on available information, the following list identifies the primary resins used to make plastic and their respective uses:[31][60]

- Low-density polyethylene (LDPE) - film and trash bags.
- High-density polyethylene (HDPE) - 1-gal milk jugs.
- Polypropylene (PP) - luggage and battery casings.
- Polystyrene (PS) - egg cartons, plates, and cups.
- Polyvinyl chloride (PVC) - siding, flooring, and pipes.
- Polyethylene terephthalate (PET) - 2-L soda bottles.

Some of these materials, most notably those containing PET resins, have been successfully recycled. However, the amount of plastic that is currently recycled is limited and there is a growing need to decrease the amount of plastics that must be disposed of in landfills.

(2) Experience

The use of polyethylene as an additive to asphalt pavements is not a new technology. These additives are generally made from virgin plastics. The only two known processes that use recycled plastic as an asphalt cement additive are Novophalt™ and Polyphalt™.(7)(31)(60) These two processes, although somewhat different, use recycled LDPE resin (generally made from trash and sandwich bags) as an additive to asphalt cement. The recycled plastic is made into pellets and added to the asphalt cement at 4 percent to 7 percent of the binder by weight of the asphalt cement (0.25 percent to 0.50 percent of the total mix by weight).(7)(60)

There is limited long-term experience with the use of recycled plastics in polymer modified asphalt cement in the United States. However, there has been a greater amount of experience with other types of virgin polymer modifiers. The success or failure of these other polymer modified asphalt cements is dependent upon a number of factors, including their compatibility with the virgin asphalts and the environment into which they are placed.(7)(60) FHWA, as part of the $150 million Strategic Highway Research Program (SHRP), is progressing toward specifications that can be directly related to performance. Once these specifications have been finalized, asphalt binders modified with recycled plastic may provide the properties necessary to conform with these specifications.

(3) Economics

Although plastic comprises about 8 percent of the total weight of the municipal waste stream, it accounts for up to 20 percent of the volume.(30)(31)(60) Thus, a small reduction by weight can produce a significant reduction in landfill volume.

Data on the cost associated with the use of recycled plastic in polymer modified asphalt cement is limited to information from the two known producers. Based on their data, incorporation of recycled plastic modifier into conventional hot mix asphalt concrete will increase the initial cost by approximately $8/metric ton ($7/ton) of mix.(60)

(4) Health and Environmental Effects

There is limited research in human health and environmental effects associated with asphalt cement modified by recycled plastics.(60) Research, performed by Novophalt™, indicates that there is no substantial difference between the HMA containing recycled plastics and conventional HMA. Further research is necessary to substantiate their findings.

OTHER RECYCLED MATERIALS

D. Blast Furnace Slag

(1) Material Availability

Blast furnace slag is an industrial by-product generated in the production of iron in a blast furnace. This slag consists primarily of silicates and aluminosilicates of lime and other bases.(36) Approximately 14 million metric tons (16 million tons) of blast furnace slag is produced annually.(31) Large accumulations of this material have been stockpiled, primarily in those States with extensive iron production plants. Although no specific environmental concerns with the production and accumulation of blast furnace slag has been identified, studies indicate that blast furnace slag should not present significant environmental problems in the form of leaching.

(2) Experience

Air-cooled blast furnace slag is an all-purpose construction aggregate. It is commonly used in concrete, HMA, aggregate bases, and as a fill material.(31) Air-cooled blast furnace slag has a number of desirable aggregate properties, including hardness, angularity, high durability, wear resistance, and low specific gravity.(61)

Research studies indicate that at least 10 States have experience using air-cooled blast furnace slag as an aggregate in asphalt pavements.(31)(36)(55)(61) The performance of these pavements has generally been good with a number of States routinely using blast furnace slag as an aggregate in HMA. Some reports indicate

limited use of air-cooled blast furnace slag in asphalt pavement due to higher than normal asphalt cement content requirements.[36]

(3) Economics

Information on the cost of disposing or stockpiling blast furnace slag was not available. Limited data on the cost-effectiveness of using blast furnace slag as an aggregate in highway construction indicates its use is either cost-effective or equal to conventional aggregates.[36] Exact cost data is not available.

(4) Health and Environmental Effects

There is limited research in human health and environmental effects associated with the use of blast furnace slag as an aggregate in HMA. Blast furnace slag has been exempted from hazardous waste status because it is classified as a mineral processing waste.[62]

E. Coal Fly Ash

(1) Material Availability

Coal fly ash, commonly referred to as "fly ash," is a by-product of coal combustion for power generation. Fly ash is generated in 720 plants in 44 States.[31] The chemical content of the fly ash varies depending on the type of coal burned. Fly ash generally contains silicon, aluminum, iron oxide, and calcium oxide. Approximately 45 million metric tons (50 million tons) of fly ash is produced annually, with 34 million metric tons (37.5 million tons) being disposed of either onsite or in State-regulated disposal areas and 11 million metric tons (12.5 million tons) being reclaimed.[63]

Environmental concerns with the continued disposal and stockpiling of coal fly ash include possible leaching of metals (such as cadmium, lead, and arsenic) into the ground water. Also, because most fly ash particles are smaller than 0.1 mm in diameter (No. 20 sieve), the waste is susceptible to erosion.[64]

(2) Experience

There has been a wide variety of experience with the use of fly ash in highway construction. In 1991, about 15 percent of DOT funds spent for concrete was spent for Portland cement concrete containing fly ash.[65] EPA's guideline for purchasing cement and fly ash requires all Federal agencies, all State and local government agencies, and contractors that use Federal funds to purchase cement and concrete to implement a preference program favoring the purchase cement and concrete containing fly ash.[32] However, its use in HMA is limited to use as a mineral filler. A mineral filler consists of the material that passes the 75-m m (No. 200) sieve and is typically between 3 percent to 6 percent of the mix by weight.[66] Mineral fillers are readily available by-products of aggregate production and the operation of baghouses in hot mix asphalt plants.

States that have used fly ash as the dust portion of a mineral filler generally have been successful.[31] However, the performance of asphalt concrete mixes is sensitive to proper aggregate gradation. To obtain proper material mix design, limits must be placed on the amount of material that passes the 75-m m (No. 200) sieve.[67] Because many aggregates contain sufficient quantities of this material, the use of fly ash as a mineral filler will be in limited amounts.

(3) Economics

Disposal costs for coal fly ash can vary substantially with the size of the power plant, the rate of operation, and the type of coal used (some coals have a higher ash content than others). In 1986, total landfill costs ranged from $2 to $7/metric ton ($2 to $6/ton) at 3,000-MW plants to $10 to $20/metric ton ($9 to $18/ton) at 100-MW plants.[64]

The cost of fly ash varies based on the location of the source. The average cost is approximately $22/metric ton ($20/ton) with a variance of $13/metric ton ($12/ton) in the Southwest to $77/metric ton ($70/ton) in the Northwest.[7] As was previously reported, average costs of fine aggregates are between $1 to $4/metric ton ($1 to $4/ton). However, coal fly ash may prove cost-effective as a mineral filler in asphalt concrete if there is a limited supply of natural aggregates that contain the desired amount of material passing the 75-m m (No. 200) sieve.

(4) Health and Environmental Effects

No information could be located that specifically addresses health and environmental effects when using coal fly ash as a mineral filler in hot mix asphalt. Of 26 States reporting on the environmental and health

risks for all uses of coal fly ash (which includes: asphalt pavement, Portland cement concrete, aggregate base coarse, subbase, or embankment), only 1 State had concerns with environmental acceptability. This State's concern was primarily due to leachate problems. The remaining States reported either "good" or "satisfactory" environmental acceptability.(36)

Fly ash is a relatively inert material that will be used as an aggregate and encapsulated in the HMA. Therefore, it could be expected that there will be no significant difference in health or environmental risks over conventional HMA.

F. Roofing Shingle Waste

(1) Material Availability

Approximately 8.6 million metric tons (9.5 million tons) of roofing shingles are manufactured each year. Approximately 65 percent of these shingles are used for reroofing, producing 5.6 million metric tons (6.2 million tons) of old waste shingles.(68) In addition, up to 800,000 metric tons (900,000 tons) of waste are produced from the manufacturing of roofing shingles annually. Typical roofing waste products, including old shingles, consist mainly of asphalt cement (36 percent), hard rock granules (22 percent), and rock filler (8 percent). There are also smaller amounts of larger [25-mm (1-in) diameter or greater] aggregates, fiber felt, glass fiber felt, asbestos felt, and polyester films.(69)

Disposal of the waste from the manufacturing process can pose a difficult problem for shingle manufacturers. Some plants are required to transport the scraps up to 500 km (300 mi) for disposal.(68) Roofing shingles, as a component of construction and demolition debris, are generally landfilled in either MSW landfills or special construction and demolition landfills.

(2) Experience

There is limited field experience in the use of roofing shingles in HMA. Currently, no long-term pavement performance data exist. A report documenting the technical feasibility of using recycled roofing shingles in asphalt pavement came to the following conclusions:(69)

- "Acceptable paving mixtures that contain 20% by volume of roofing wastes can be produced. With proper selection of binder type, binder quantities, and aggregate gradations acceptable mixtures containing roofing waste quantities to, and perhaps beyond, the 30% level can probably be prepared."
- "The type of binder selection for use in a mixture containing roofing waste should be based on the stiffness (penetration and viscosity) of the asphalt cement in the roofing waste."
- "Improved asphalt extraction and recovery processes need to be developed for roofing waste in order to effectively determine the properties of the asphalt cement in the roofing waste."
- "Gradation of conventional aggregates and roofing waste should be considered when designing the paving mixtures."

The Minnesota Department of Transportation completed a project in 1991 that used from 5 percent to 7 percent asphalt shingles by weight of mix.(70) The shingles were ground to a uniform consistency resembling coffee grounds and were then added to a drum mix plant as if they were RAP. No construction problems were noted. After less than 2 years, there have been no reported problems with pavement performance. Other pavement sections have also been constructed in Florida with good results.(68)

(3) Economics

Based on information provided by the Minnesota Department of Transportation, shingles used for the test project were being disposed of by the manufacturer in landfills at a cost of $21/metric ton ($19/ton). For this project, the shingle producer paid the processor the same $21/metric ton ($19/ton) to take ownership of the roofing shingle waste. Based on an estimate provided by the contractor, it cost $9.55/metric ton ($8.65/ton) for processing and transportation of the shingles to the project site. Assuming the shingles contained 30 percent asphalt, a savings was also realized in a reduction in the amount of asphalt required for the mix. Overall, adding roofing shingles to the asphalt pavement increased the cost by $23/metric ton ($21/ton). This was due primarily to the additional negotiated costs associated with changing the mix design after award of the project.

Other data indicates that roofing shingle waste can

cost up to $66/metric ton ($60/ton) for disposal. Landfills are charging between $20 to $50/metric ton ($18 to $45/ton) to accept old roofing shingles.(68) Based on these figures, an asphalt cement cost of $130/metric ton ($120/ton), and an aggregate cost of $8/metric ton ($7/ton), using 5 percent roofing shingles by weight in an asphalt mix can save up to $3.08/metric ton ($2.79/ton) over conventional HMA.

(4) Health and Environmental Effects

Research on the human health and environmental effects of using roofing shingle waste in asphalt pavements is not available. Since these wastes contain the same basic materials as conventional asphalt pavements, there should be no significant difference in any health or environmental risks, provided the recycled shingles do not contain asbestos.

G. Mining Wastes

(1) Material Availability

Approximately 1.6 billion metric tons (1.8 billion tons) of mineral processing wastes are produced annually in the United States.(31) The three types of mineral processing wastes that have been used in asphalt pavements are waste rock [0.9 billion metric tons/year (1 billion tons/year)], mine tailings [450 million metric tons/year (500 million tons/year)], and coal refuse [110 million metric tons/year (120 million tons/year)]. Past mining activities have accumulated mountainous stockpiles of these materials. Each of these materials has its own specific environmental problems, but can generally be summarized as follows:(61)(71)

- Acidic drainage from both coal and metal mining waste that in turn promotes leaching of heavy metals into surface and ground water.

- Radiation hazards from uranium mill tailings.

The availability of these materials is dependent upon the location of the mining activity, which is typically located in remote geographical areas.(61)

(2) Experience

There has been a wide range of experience with the use of the various mining wastes in highway construction.(31) Their use as an aggregate in asphalt concrete mixes depends upon the type of mineral waste used. Research indicates that four States have used mine tailings in asphalt pavements, primarily to improve skid resistance, with good to excellent results.(31) The burning of coal refuse produces a material called "red dog" that has also been used successfully in asphalt pavements. The major deterrent to using these materials in highway construction projects is the increased cost associated with transporting them to the construction site.(61)

(3) Economic Concerns

Information on the costs associated with the disposal of stockpiling mining waste was not available. The cost of incorporating mining waste into an HMA pavement will depend on a number of factors, including selling price, transportation costs, and processing costs.(61) Experience has shown that when economically viable, these products have been used in asphalt concrete pavement projects.

(4) Health and Environmental Concerns

Research on the health and environmental effects of using mining waste in asphalt pavements was not available.

H. Municipal Waste Combustion Ash

(1) Material Availability

In 1980, 2.4 million metric tons (2.7 millions tons) of MSW was burned, resulting in approximately 800,000 metric tons (900,000 tons) of municipal waste combustion (MWC) ash or residue.(30) In 1990, this figure jumped to 29 million metric tons (32 million tons) burned and approximately 7 million metric tons (8 million tons) of MSW ash or residue.(30) Between 80 percent and 99 percent of this ash is bottom ash with the remainder being fly ash.(36) The requirements for disposal of MSW ash will vary by State with some States classifying it as a hazardous waste. At the present time, EPA officials estimate that less than 10 percent of the MWC ash produced is being used in a limited number of beneficial-use projects.

(2) Experience

A study was done in 1978 by Teague and Ledbetter on the performance of using incinerator residue in an

asphalt concrete base course.(72) The project was constructed in Houston in 1974 and performance data were collected after 3 years of use. The results indicated the asphalt base course performed in an excellent manner, almost identical to the conventional asphalt pavement section. The mix design used 89 percent incinerator ash, 9 percent asphalt, and 2 percent lime (as an anti-stripping agent) by weight of mix. A project in Washington, DC, was constructed with 50 percent incinerator ash and 50 percent natural aggregates and showed promising results.(73) Other test sections have also been placed with satisfactory performance results.(31)

(3) Economics

In 1979, FHWA published a report that evaluated the economic and environmental feasibility of using incinerator residue in highway construction.(73) The report analyzed data from five Standard Metropolitan Statistical Areas and included costs associated with purchasing the materials, transporting the materials, processing the materials, if necessary, and any savings in landfill costs. As a result of this study, the following was concluded:

"When landfill cost savings associated with incinerator residue used for highway construction are taken into account, economic analysis shows that unfused incinerator residue is strongly viable as a bituminous highway construction material."

(4) Health and Environmental Effects

Currently, the health and environmental effects of beneficial use of MWC ash are being researched. No conclusions have been reached.

I. Steel Slags

(1) Material Availability

In 1989, approximately 7 million metric tons (8 million tons) of air-cooled steel slag were produced in the United States.(31) Steel slag is a by-product from producing steel and the amount of slag can vary considerably based on the different types of steel furnaces used.(61) The basic constituents of steel slag are fused mixtures of oxides and silicates, primarily calcium, iron, unslaked lime, and magnesium.(31) Research indicates that steel slag should not present significant environmental problems in the form of leaching.(61)

(2) Experience

Steel slags are highly variable materials that have been shown to have a potentially expansive nature.(36)(74) Steel slag is a fairly well-graded material with a top size of about 20 mm (3/4 in), with from 3 to 10 percent passing the 75-m m (No. 200) sieve; however, for use as an aggregate in asphalt pavements, it will need to be regraded or blended with natural aggregates.(74) The Collins survey reports that eight States have experience with steel slag in asphalt concrete.(31) Though Collins reports mixed success with steel slags, it should be emphasized that different steel plants will produce slags with different properties.(61)

One of the major problems associated with the performance of steel slags is their expansive nature.(74) The above-referenced reports lead to the conclusion that some steel slags may be acceptable for use as an aggregate in asphalt concrete pavement, provided care is taken to ensure that the slag is subjected to a controlled curing process of about 6 to 12 months.

(3) Economics

Research on the cost to dispose or stockpile steel slags was not available. Current information on the exact costs associated with incorporating steel slags into asphalt concrete pavements was not available. Studies on the use of steel slag as an aggregate in highway construction indicate that of the limited number of States indicating usage, the initial cost of steel slags are comparable with other aggregate sources.(36)

(4) Health and Environmental Concerns

Limited research is available on the health and environmental effects of using steel slags in asphalt pavements. Of the five States reporting on the environmental and health risks for all uses of steel slag (which includes HMA pavement, Portland cement concrete, aggregate base course, subbase, or embankment), one State had concerns over possible leachate problems. The remaining States reported either "good" or "satisfactory" environmental acceptability.(36)

J. Reclaimed Concrete Pavement

(1) Material Availability

It is estimated that approximately 3 million metric tons (3 million tons) of concrete pavement is being recycled annually.[75] The remaining amount of concrete pavement rubble that is not recycled is generally considered a waste material and is disposed of in landfills or other disposal sites. However, at least one State (Florida) does not allow the disposal of construction debris in its landfills.[31]

(2) Experience

Reclaimed concrete can be crushed or rubblized and used as an aggregate source. The recycled aggregate can be used in a subbase, base, stabilized base, Portland cement concrete, or asphalt concrete. Concrete recycling basically consists of breaking up the pavement, hauling broken pieces to a crushing plant, crushing and processing the broken concrete to appropriate sizes, and stockpiling the processed material for use in its end product. Recycled concrete aggregate will usually meet specification requirements for conventional aggregates, although its widespread usage is not documented. Florida and Illinois have been reported as using recycled concrete aggregate in hot mix asphalt. Two States have performed research on the use of reclaimed concrete as an aggregate in hot mix asphalt and one State is planning on conducting research.[31] Collin's survey indicated that its most common usage was as an aggregate subbase or base course.

(3) Economics

The first cost savings for using reclaimed concrete as aggregate is dependent on: availability and haul length of virgin aggregates, location of existing pavement, haul length to crushing plant, and haul length to end user. Typical crushing costs average approximately $3.30/metric ton ($3.00/ton), while hauling costs an average of approximately $0.10/metric ton-km ($0.15/ton-mi). The first cost savings from using recycled concrete aggregate is offset a little by the increase in asphalt cement that is required by the highly absorptive material.[76] Recycled concrete aggregate normally requires 0.5 to 1.0 percent more asphalt cement than most conventional aggregates.

(4) Health and Environmental Concerns

The health or environmental effects of incorporating reclaimed concrete into asphalt pavements have not been studied. However, it is reasonable to conclude that additional stack emissions or leachate would not be a problem due to the inert nature of the concrete.

K. Sulfur

(1) Material Availability

Sulfur is an important industrial raw material. Though elemental sulfur has been mined, the current major sources of sulfur are now a by-product of natural gas "sweetening" and refinement of petroleum and tar sands.[77] The availability of sulfur is greatly dependent on the world market and estimates regarding the amount of sulfur stockpiled at any one time can vary from very little to millions of metric tons.

(2) Experience

From 1977 to 1982, 26 projects in 18 States were constructed using sulfur as an extender to asphalt cement [sulfur extended asphalt (SEA)] in asphalt paving mixtures. Sulfur was substituted for asphalt binder in these mixes at a rate of 20 percent to 40 percent by weight. In 1987, a field study was undertaken by FHWA to determine the performance of these pavement sections.[78] Based on the results from this report, it was concluded that the overall performance and susceptibility to distress are not significantly different for SEA pavements than for closely matched control sections of conventional asphalt pavements. It also stated that, as a group, the SEA pavements show a significantly smaller incidence of transverse cracking than the AC pavement control group.

(3) Economics

The cost associated with the use of sulfur as an additive to asphalt pavements will depend on the market cost of the sulfur. Based on results from a study completed by the Washington State Department of Transportation, sulfur is a cost-effective substitute for asphalt when the market price of asphalt is greater than 1.7 to 1.8 times the market price for sulfur.[77] Due to the high variability in the cost of sulfur, it is not typically substituted for asphalt cement.

(4) Health and Environmental Concerns

In 1980, a study was undertaken by the Arizona Department of Transportation in cooperation with FHWA and the U.S. Bureau of Mines to determine if SEA concrete could be safely and efficiently produced in a drum mix plant.(79) The study examined both stack emissions and worker health and safety. Results from this study indicated that for health and worker safety, no harmful emissions of either H_2S or SO_2 were reported.

Results from stack emission testing results indicated that the sulfur gaseous emissions were far in excess of those for conventional asphalt (78 to 84 ppm vs. 469 ppm).(79) The emissions were similar to those emitted by power plants burning low-sulfur coal without sulfur emissions control. Without some type of emission control system, such as a wet scrubber, this amount of emissions may exceed air quality standards downwind.

CURRENT DISPOSAL PRACTICE

State legislatures throughout the Nation have expressed concern over the increasing amounts of waste materials that are being produced. This concern has resulted in several types of legislation aimed at reducing the generation of waste and promoting recycling.

By 1992, 39 States had some form of statewide law encouraging or mandating recycling.(80) Every State has passed legislation promoting the procurement of certain products (often paper products) using recycled materials by State agencies and their contractors. At least two States require highway construction projects to use recycled materials. Thirteen States have legislation requiring minimum contents of recycled materials in certain products (often newspaper), while an additional 11 States have voluntary agreements with the same goal.

Though there are many possible waste products produced during the construction of highways, the greatest quantity comes from the removal or replacement of the existing pavement structure. Not surprisingly, these are also the materials that are most often recycled or reused.

The appended research synthesis report contains a survey of SHA's on their current reuse/recycle/disposal practices.(7) A summary of this survey is provided in table 5. Based on this survey, the most commonly recycled or reused material is RAP. Of the 29 SHA's responding to the survey, only Minnesota reported that it disposed of all RAP. Although Minnesota reported that 100 percent of the material was disposed of, this value is misleading. Minnesota, as is the case with many SHA's, makes this material the property of the contractor, who may reuse, recycle, or dispose of the RAP. The Minnesota highway construction specifications allow the contractor to reuse this material (at a rate of up to 60 percent by weight) in a State-approved recycled asphalt pavement or other recycled pavement projects.

As was previously reported, many States are recycling or reusing reclaimed concrete pavements. The uses for reclaimed concrete pavement include aggregate for reuse in: asphalt or concrete pavement, subbase or unbound base courses, or as a slope stabilization material (i.e., rip-rap).

Aggregates, including base courses, subbases, and shoulders are also primarily reused or recycled. Many States reuse or recycle old guardrail systems including the rail itself or the steel posts. The refurbishing of sign faces for reuse is a common practice among many States. Most States surveyed also reported experience with the reuse or recycling of steel girders removed from reconstructed bridges.

TABLE 5. **SUMMARY OF DISPOSAL PRACTICES**

	Average Percentage of Material	
Material/Appurtenance Type	Disposed (1)	Reused/Recycled (2)
Asphalt Concrete: Surface Course	16	82
Base Course	16	82
Stabilized Base	27	65
Crushed Stone	16	67
Crushed Gravel	19	77
Granular Subbase	22	73
Stabilized Subbase	26	50
Shoulders, Asphalt	22	74
Concrete Culverts	74	22
Corrugated Steel Pipe Culverts	87	13
Wood Culvert	100	0
Multiplate Underpass or Culvert	66	26
Guard Rail	48	52
Guard Rail Posts (Steel & Wood)	54	42
Signs - Advisory and Regulatory	47	53
Sign Posts	56	44
Sign or Signal Pole and Structures	54	44
Bridges: Aluminum or Steel Railing	56	44
Steel Superstructure & Deck	63	37
Concrete Beams	83	12
Concrete Deck	89	11

(1) These materials may be buried on the project, landfilled, sold as scrap material, and/or disposed of as contractor property. These materials may be reused or recycled in non-highway applications.

(2) These materials are functionally reused or recycled in highway projects.

CHAPTER 4 - SUMMARY AND CONCLUSIONS

Section 1038(b) of ISTEA calls for the Secretary of DOT and the Administrator of EPA to conduct studies to determine: (A) the threat to human health and the environment, (B) the recyclability, and (C) the performance of asphalt pavement containing CRM. The study also directs the examination of the use of other waste materials in highways. Section 1038(d) requires the minimum utilization of tire rubber in asphalt paving materials beginning in 1994.

This study evaluates available data regarding the various engineering, health, and environmental aspects of working with asphalt pavement containing recycled rubber. In addition, other recycled materials applications were specifically evaluated: reclaimed asphalt pavement, asphalt pavements containing recycled glass, asphalt pavements containing recycled plastics, and others. The initial phase of the studies required by section 1038 is complete and we have developed a synthesis of all available information.

SCRAP TIRE RUBBER

A. Health/Environmental Assessment

The weight-of-evidence from the currently available information shows that the emissions from any asphalt plant, either producing conventional HMA or CRM HMA, can vary widely, both in the profile of emissions observed and in the levels of each contaminant released. Based on the findings from seven projects in the United States and Canada, the currently available data collectively indicate that no obvious trends of significantly increased or decreased emissions can be attributed to the use of CRM in HMA pavement production.

The finding of MIBK in CRM asphalt pavement mixtures in three out of seven studies may warrant further investigation. An evaluation of the most exposed human population, workers involved in the production and construction of asphalt pavements containing CRM, indicates no obvious basis for concern of increased risk to this population, based principally on an analysis of emission data.

In summary, using the currently available information, we find there is no compelling evidence that the use of asphalt pavement containing recycled rubber substantially increases the threat to human health or the environment as compared to the threats associated with conventional asphalt pavements. These findings are based on the limited available data from a few studies. These conclusions are subject to revisions as additional information is obtained and evaluated.

B. Recycling

Based on the results of two projects where asphalt pavements containing CRM were recycled, the available literature, and an evaluation of variability in plant configurations and operations, this technology appears to be constructible as a recycled pavement. To date, these two recycled pavements are performing comparably to existing hot mix asphalt pavement. However, sufficient information regarding long-term performance and economics is not available. These two projects represent an extremely limited perspective of the variability of in-service pavement properties, environmental conditions, varying asphalt cements and mixtures, and asphalt plant configurations and operations. However, there is no reliable evidence that asphalt pavements containing recycled rubber cannot be recycled to substantially the same degree as conventional HMA pavements.

Additional evaluations are contemplated and will be required to develop further criteria for recycling CRM asphalt pavements. A national pooled-funds study has been initiated. Thirty-three States will participate with FHWA and EPA to further evaluate recycling of CRM pavements. Requests for proposals for this pooled-fund research effort will be solicited this fiscal year (1993).

C. Performance

While pavements containing CRM have been constructed and have been in service for as many as 20 years in Arizona, California, and a few other States and based on an extensive review of available literature and project data, only limited information on engineering and economic performance is available. This is due to limited documentation, experimental evaluation, and a resulting incomplete data base upon which to conduct long-term performance evaluations. While other States have conducted limited experimental research with CRM technologies, the performance of asphalt pavements containing recycled rubber has received only limited evaluations under varied climatic and use conditions.

In order to develop a reliable cost and economic evaluation of pavements containing CRM, comparable information must be developed on the construction of CRM asphalt paving projects of typical size rather than experimental applications. The performance to date on the CRM projects has been mixed, some experiencing early failure, others performing comparably to conventional asphalt pavements, and some CRM pavements have performed better than conventional mixes. Due to limited documentation, the exact cause of the premature distress in CRM pavements has not been established. However, when properly designed and constructed, there is no reliable evidence to show that pavements containing recycled rubber will not perform adequately as a paving material.

We will continue national research on CRM technologies to develop reliable engineering and economic criteria for the CRM pavements. Additionally, many States are conducting coordinated research to evaluate the effects of local conditions and materials. The results of these studies will be included in long-term performance evaluations.

OTHER RECYCLED MATERIALS

In the last 30 years, the generation of solid waste in the United States has increased twofold. This increase coupled with the concern of society regarding environmentally safe and efficient disposal of these materials dictates the need to find alternative uses. Economic and engineering alternatives for reuse of waste products in highway applications should continue to be identified, evaluated, and developed.

The highway community pioneered the use of waste materials beginning with asphalt, a waste product of the crude oil refining industry. A long history of incorporating by-products and waste materials exists today. Recycling of asphalt pavements has received extensive use in the United States since the mid-1970's. Current recycling practice today is determined by the availability of suitable materials, economic costs, and performance.

Studies were conducted on the use and application of waste products within the highway environment. A wide array of ideas, concepts, and applications for waste products exist. Documentation on environmental and human health risks, engineering criteria, costs, economic savings, and performance varies from limited to extensive, depending on the material and application. Only limited information on the environmental benefits of using these materials in highway applications exists today.

A. Reclaimed Asphalt Pavement

Most State highway specifications permit the contractor to incorporate a percentage of RAP into asphalt pavements to the extent the recycled HMA meets existing specifications for new materials. In the United States, over 80 percent of the asphalt pavement removed is reused in highway applications.

Current asphalt pavement recycling practices utilize 10 to 22 percent RAP in recycled HMA production using conventional hot mix plant technology. State-of-the-practice conventional technology has demonstrated the capability to recycle asphalt pavements at a maximum of 50 to 70 percent RAP for properly engineered hot mix materials without adverse engineering or environmental problems. The exact percentage of RAP that can be successfully incorporated into a given recycled mix is dependent on the in-service pavement materials properties and field conditions. Recycling, as a pavement rehabilitation technique, generally will not enhance the basic materials properties of the pre-existing pavement. To meet materials engineering criteria for many recycled mixes, RAP is often included at a lower percentage than the maximum percentage at which a conventional HMA plant can operate efficiently and continue to meet environmental standards. Hot in-place recycling has been developing since the mid-1970's. Hot in-place recycling has been performed on asphalt pavements using in excess of 80

percent RAP, but the results have been aging of the asphalt cement and excessive emissions. New technology is under development to address this problem. Cold recycling has been used successfully on medium- to low-volume roads to recycle 100 percent RAP. Microwave technology is now available that has demonstrated the capability of hot recycling of asphalt pavement within current emissions standards at RAP percentages of 80 percent and greater. This technology has had only limited utilization to date and is proprietary.

HMA pavements utilizing 80 percent RAP produced with conventional hot mix technology result in early aging and oxidation of the asphalt cement and unacceptable air quality emissions. Cold-mix recycling has been performed successfully for in-place and central plant production. Comprehensive information on the performance of cold in-place recycling is not available and life-cycle costs have not been determined. Mixture design and analysis procedures are limited and require further development. Paving projects constructed utilizing microwave technology are performing satisfactorily to date.

State highway agencies report a cost savings when using RAP. Recycling of asphalt pavements using various percentages of RAP is a proven technology and with proper engineering and mixture design, recycled HMA can be considered an appropriate substitute material as provided for under subsection 1038(d)(2) of ISTEA.

Additional information on the use of RAP at the 80 percent or greater level for the various recycled asphalt mix production technologies is needed for long-term performance, engineering design, economics, and environmental and human health impacts. FHWA will continue to develop and advance this technology as a viable alternative reuse resource.

B. Recycled Glass

Glass is a significant component in the solid waste stream. It is highly suitable for solid waste recycling. Its use as a substitute paving material has been demonstrated. The economics of using waste glass are highly dependent upon availability. In general, large quantities of waste glass are found primarily in major metropolitan areas. The analysis indicates limited potential for risks to human health and the environment.

Significant literature and experimental project data are available to support the use of recycled glass in properly engineered asphalt pavement mixtures up to 15 percent. Thus, the addition of recycled glass into HMA mixtures can be considered as an appropriate substitute material as provided for under subsection 1038(d)(2) of ISTEA.

C. Recycled Plastic

Like glass, plastic is also a significant part of the solid waste stream. However, only limited reuse of waste plastics exists today. Plastics in the waste stream vary significantly in chemical composition. To date, we have extremely limited experience with the use of recycled plastics in highway applications. The use of plastics as a polymer modifier in asphalt pavements exists today. While there are several technologies available to blend virgin plastics with asphalt cements to produce a polymer modified binder, the chemical variability in recycled plastics has been a significant deterrent to the use of waste plastics in pavements. Two known HMA paving products that utilize waste plastics exist. Only limited performance, economic, and environmental data are currently available. Therefore, the use of recycled plastics in asphalt pavements is not considered an appropriate substitute material under subsection 1038(d)(2) of ISTEA at this time. We will continue to work with the States and industry to evaluate the emerging asphalt paving products and applications.

Based on the review, we have identified other potential highway applications for reuse of recycled plastics. We will continue to develop and promote the use of these technologies as appropriate.

D. Other Recycled Materials

Our research revealed many potential applications for reuse of waste and by-product materials within the highway setting. Only limited information is available for many of these waste products. A waste materials symposium, "Recovery and Effective Reuse of Discarded Materials and By-Products for the Construction of Highway Facilities," is scheduled for October 1993. The objective of this symposium is to identify and disseminate current state-of-the-art information on new and innovative methods for effective recycling and reuse of waste by-products within the highway system.

Other waste materials identified as currently applicable for use in asphalt pavements include coal fly ash, blast furnace slags, reclaimed concrete pavement, and waste rock. With proper materials mixture design, these materials would be an acceptable substitute material as provided for in subsection 1038(d)(2) of ISTEA.

Several other materials were identified as having potential asphalt pavement applications, but we have inadequate information or performance experience with these materials at this time. These include coal bottom ash, non-ferrous slags, steel slags, roofing shingles, and mine tailings.

CURRENT DISPOSAL PRACTICES

A majority of the States have some form of statewide law encouraging or mandating recycling or reuse of waste materials. Current practices by the State highway agencies regarding the reuse and disposal of materials in federally assisted highway projects vary. All States responding to our survey practice reuse of waste materials where technically and economically feasible. The results of our survey are summarized in table 5.

CONCLUSIONS

Highway agencies across the United States have recognized the importance that the highway system plays in providing for an improved environment.

Significant contributions are being made in current recycling practices. Additional development is underway to identify and develop opportunities to reduce highway waste generation and increase recycling and reuse where technically and economically feasible. Major investments in developing environmental, health, engineering, and economic performance criteria and guidance are underway.

Based on the studies to date and limited project data available:

- There is no reliable evidence indicating that the manufacture, application, or use of asphalt pavement containing recycled rubber substantially increases the threat to human health or the environment as compared to the threats associated with conventional hot mix asphalt pavements.
- There is no reliable evidence that asphalt pavements containing recycled rubber cannot be recycled to substantially the same degree as conventional pavement.
- There is no reliable evidence that asphalt pavement containing recycled rubber does not perform adequately as a material for the construction or surfacing of highways and roads.

Additional research is underway to continue to develop our understanding of factors influencing the reuse of waste products within the highway system and to develop sound environmental, economic, and engineering criteria.

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